Reconstruction of $B_s^o \to J/\Psi\,\eta'$ at LHCb experiment and sensitivity to ϕ_S and $\Delta\Gamma_s/\Gamma_s$

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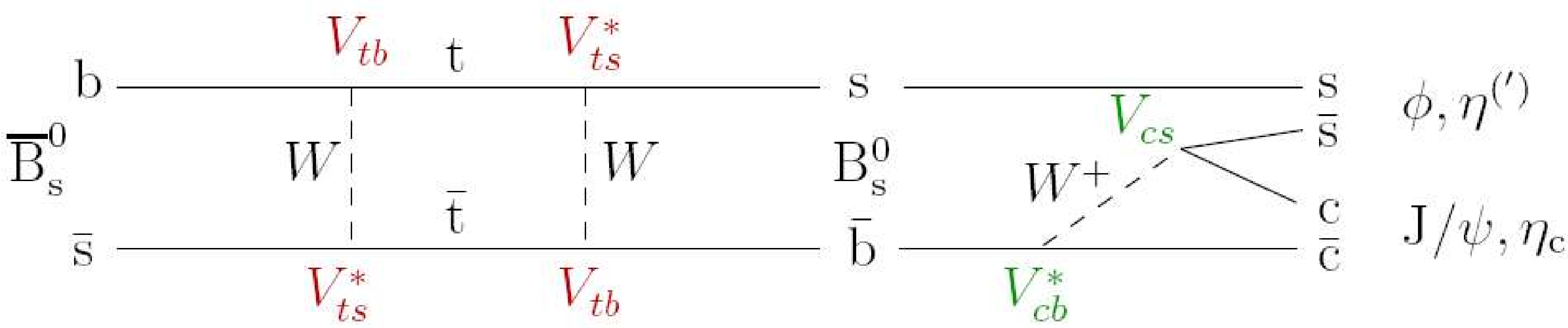
Outline

- Mixing-induced CP violation
- Physics motivations
- $\bar{b} \to \bar{c}\, c\, \bar{s}$ transitions
- Off-line selection of $B_s^o \to J/\Psi\,\eta'$; selection cuts
- Annual yield and background levels.
- Sensitivities studies
- Conclusions

Mixing-Induced CP violation.

- B_s^o - $\bar{B}_s^o$ system will serve to test CP violation in standard model (SM) .
- B_s^o, $\bar{B}_s^o$ flavors can either oscillate into each other or decay to final state.
- Mixing-Induced CP violation results from phase mismatch between weak mixing phase ϕ_S and decay phase ϕ_D .



- In $\bar{b} \rightarrow \bar{c}\, c\, \bar{s}$ quark level transitions we have direct access to mixing phase ϕ_s via mixing-induced CP asymmetry.

$$\mathcal{A}_{\rm CP}^{th}(t) = \frac{-\eta_f \sin(\phi_s)\sin(\Delta M_s t)}{\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \eta_f \cos(\phi_s)\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)}$$

- Mass and decay width differences between "heavy" & "light" mass eigenstates:

$$\Delta M_q \equiv M_H - M_L \qquad \Delta\Gamma_q \equiv \Gamma_H - \Gamma_L \quad \text{where } q \in [s, d]$$

$$|B_{L/H}> = p|B_s^0> \pm q|\bar{B}_s^0> \qquad \Gamma_q = \frac{(\Gamma_H + \Gamma_L)}{2} \quad \text{(average)}$$

- $B_d^o - \bar{B}_d^o$ (Well measured)
- $\Delta M_d \sim 0.5 ps^{-1}$
- $\Delta\Gamma_d / \Gamma_d \sim 0$
- $\phi_d \equiv 2 arg[V^*_{td} V_{tb}] \approx 2\beta = O(0.8 rad)$

- $B_s^o - \bar{B}_s^o$ (Terra incognita)
- $\Delta M_s \sim 20 ps^{-1}$ ~ 40 times faster than B_d
- $\Delta\Gamma_s / \Gamma_s \sim 10\%$ Sizeable
- $\phi_s \equiv 2 arg[V^*_{ts} V_{tb}] \approx 2\beta_s = O(-0.04 rad)$

- Physics Motivations: Measure mixing parameters ϕ_s and $\Delta\Gamma_s/\Gamma_s$

$\bar{b} \rightarrow \bar{c}\, c\, \bar{s}$ transitions

- B_s^o decays into CP self-conjugate final states caused by $\bar{b} \rightarrow \bar{c}\, c\, \bar{s}$ quark level transitions.

$B_s^o \rightarrow J/\Psi\, \phi$

- Admixture of CP eingenstates (+1,-1,+1)
- Need angular analysis to disentangle them
- High no. of selected events
- Low B/S ratio

$B_s^o \rightarrow \eta_c\, \phi,\ \ B_s^o \rightarrow J/\Psi\, \eta^{(\prime)}$

- pure CP-even eingenstates (+1)
- No angular analysis
- Low no. of selected events
- Worse B/S ratio

- Channels with photons & high multiplicity get worse resolutions

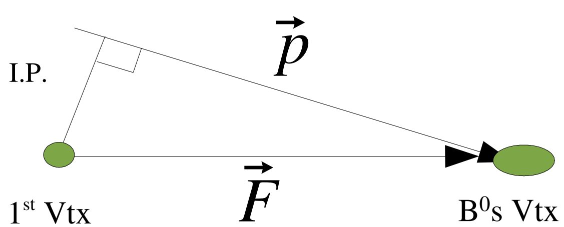
$B_s^o \to J/\Psi\, \eta'$ off-line selection at LHCb experiment: Selection Cuts

- Off-line selection studied with full MC simulated data, both for signal and background.

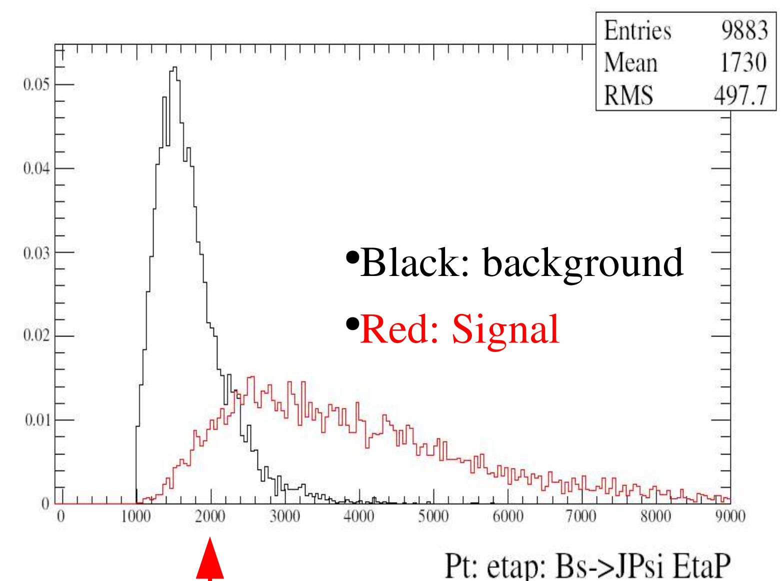
 [p-p collisions, decays, LHCb detector, response, trigger systems etc. are fully simulated]

- To select $B_s^o \to J/\Psi(\mu^+ \mu^-)\eta'(\pi^+ \pi^- \eta(\gamma\gamma))$ a set of topological and kinematical cuts are defined to remove bad combinations.

- E, P thresholds are applied to end-products, ~3σ in mass resolutions, max. IP and min. Flight distance cuts for B0s candidates w.r.t production vertex.



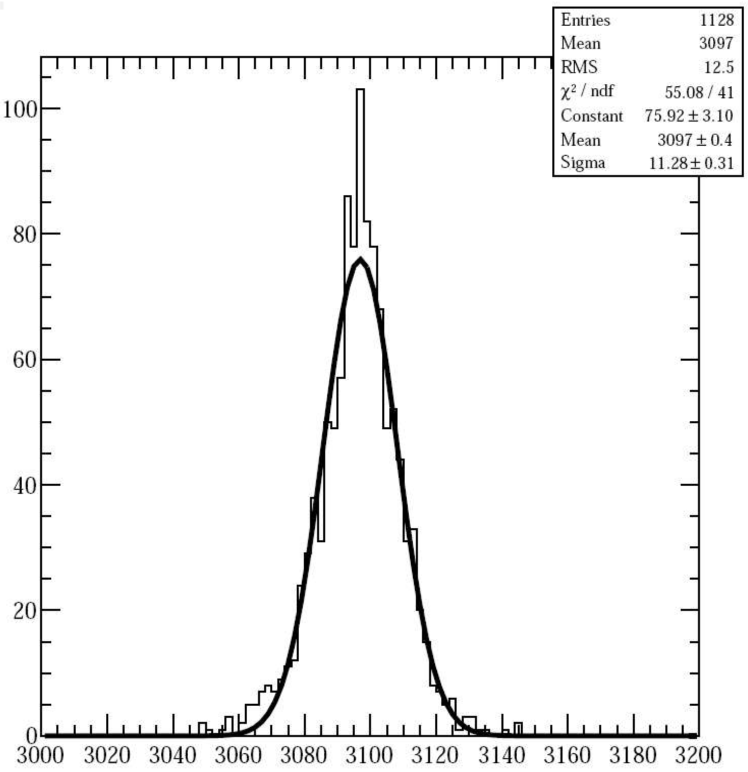
where **F,** is flight vector and **P,** B^0s candidate momentum vector



Example of cut: Pt of η' candidates

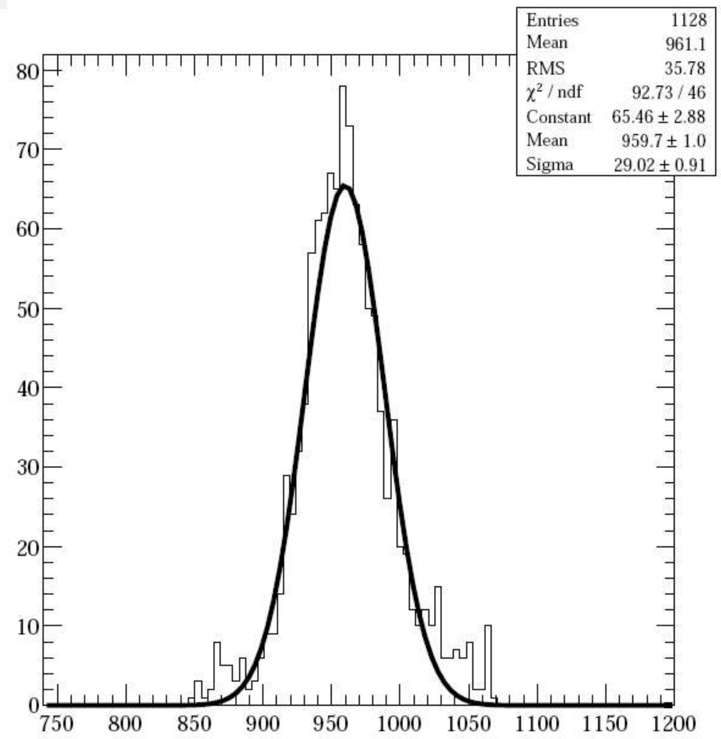
- These cuts are optimize in order to reduce any possible sources of background events.

$B_s^o \rightarrow J/\Psi\,\eta'$ off-line selection at LHCb experiment: Mass Distributions



Mean(J/Ψ) ~ 3097 **MeV/c²**

σ ~ 11 **MeV/c².**



Mean(η') ~ 960 **MeV/c²**

σ ~ 29 **MeV/c².**

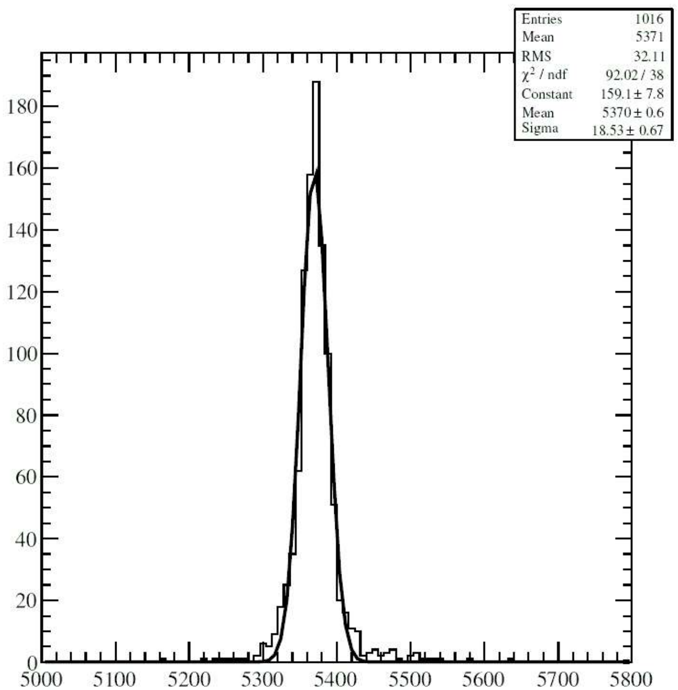
- After selection, we see that our eta' distribution is wide due to poor resolutions of photons

$B_s^o \rightarrow J/\Psi\,\eta'$ off-line selection: Mass & Lifetime distributions

- After selection of B^0_s candidates apply Kalman fit to refine selection and improve mass resolutions:

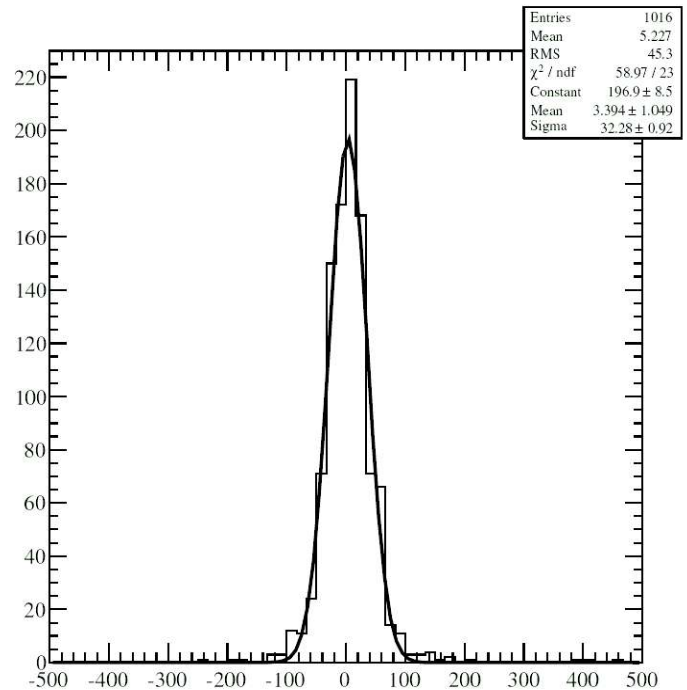
Kalman Fit: Refines the fit by using a recursive method which properly take into account the errors of the 4 vectors for the photons.

- Lifetime and its error estimated by LS fit to the observables.



Mean ~ 5370 MeV/c². σ ~ 19 MeV/c².

Kalman Fit



Lifetime Resolution(B_s):

(32.3 ± 0.9) **fs [Kalman Fit]**

$$c\cdot\tau = m_{B^0_s}\frac{\vec{p}_{B^0_s}\cdot\vec{L}}{\left|\vec{p}_{B^0_s}\right|^2}$$

Where $\vec{L}=\vec{x}_s-\vec{x}_p$

B^0_s meson flight distance w.r.t. primary vertex

Flavor tagging:

- When a signal B is reconstructed we need to know its initial flavor. [See Jeremie Borel's talk]

Procedure not always gives answer: tagging efficiency ϵ_{tag}

Tag given could be incorrect: ω. Wrong tag fraction.

Triggers:

- Three levels of triggers to leave only events of interest; Level 0,1, HLT [See Jeremie Borel's talk]

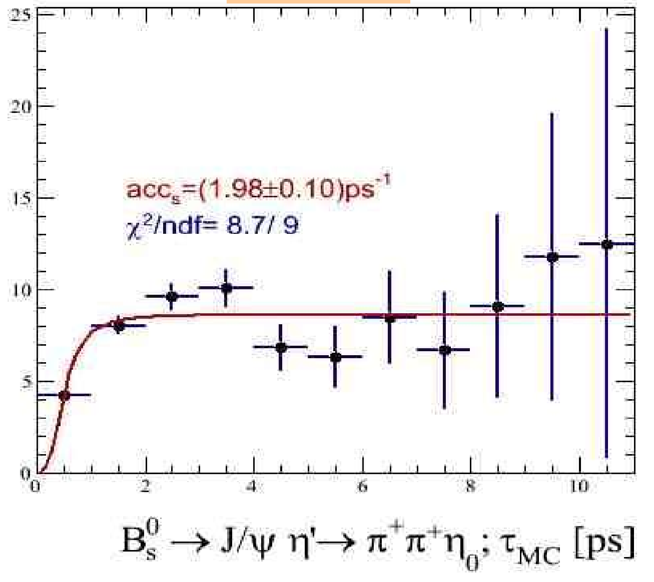
Acceptance function:

Bias on the proper time distribution due to selection cuts.

$$\varepsilon_{\tau} = acc_a \cdot \frac{acc_s \cdot t^3_{MC}}{1+acc_s \cdot t^3_{MC}}$$

Where acc_s is the slope at low proper time

After HLT



Comparison of decay channels - from full MC simulation

Event yield: • Number of $B_s^o \rightarrow J/\Psi\ \eta'$ events for physics studies per year ($2fb^{-1}$):

Yield = N_{B0s} * $B.R._{vis}$ * ϵ_{tot}

- $B.R.(B_s^0 \rightarrow J/\psi\ \eta')$ branching ratio estimated by U-spin symmetry w.r.t $B.R.(B_d^0 \rightarrow J/\psi\ K^0)$
- $|\eta'> = |\eta_8> sin\theta_p + |\eta_1> cos\theta_p$

Pseudoscalar mixing angle θ_p estimated to be [-20°, -10°] $(Mixing\ Angle: \theta_p = -15°)$

- Main source of background to compute B/S is $b\bar{b}$ -inclusive.

Parameters	$J/\psi\eta(\gamma\gamma)$	$J/\psi\eta(3\pi)$	$\eta_c\phi$	$J/\psi\eta'(\eta\pi\pi)$	$J/\psi\phi$
Untagged yield[k events]	8.9	3.1	3	2.15	125
B/S	2.00	3.00	0.70	1.98	0.80
acc_slope	1.9	1.5	1.3	2	2.9
σ(Bs)[MeV/c2]	34	20	12	19	14
ω / ϵ tag	35/63	30/62	31/66	31/64	33/65

$B^o_s \to J/\Psi\,\eta'$: ϕ_s sensitivity studies

- The "golden channel" for the studies of ϕ_s mixing phase is: $B^o_s \to J/\Psi\,\phi$

Has very good mass and proper-time resolutions, high number of events selected and background levels very low.

BUT, it requires angular analysis to disentangle the odd and even contributions.

- Can the pure CP eigenstates channels help in the determination of ϕ_s mixing phase?
- Using decays like $B^o_s \to \eta_c\,\phi$, $B^o_s \to J/\Psi\,\eta^{(\prime)}$ we hope to (significantly) improve ϕ_s sensitivity of the LHCb experiment.

- Number of events that we can generate in a full Monte Carlo simulation quite low, due to CPU and Storage limitations. Sensitivities Assessed by means of (Fast) Toy MC simulations.

✓ Input parameters obtained from full MC:
(acc_s=2.0 ps^{-1} // B/S= 2 // Signal Yield = 2000.0 // ω=31% // ϵ_{tag}=63%)

✓ Nominal parameters for physics. (τ=1.472ps^{-1},ϕ_s=-0.04 rad,ΔM_s=20ps^{-1},$\Delta\Gamma_s/\Gamma_s$=10%)

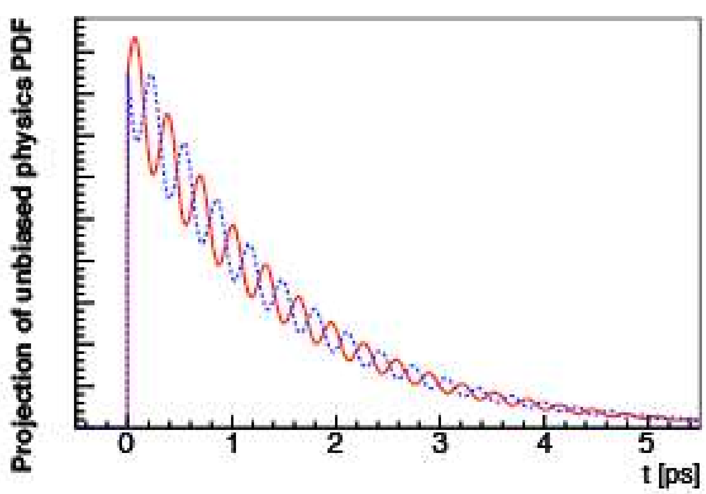
- Transition rates of initially pure B_s^o and $\bar{B}_s^o$ states.

$$R\left(\mathrm{B_s^0}(t) \to f\right) = |A_f(0)|^2 \times e^{-\Gamma_s t} \times \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \eta_f \cos(\phi_s) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + qD\,\eta_f \sin(\phi_s) \sin\left(\Delta M_s t\right)\right]$$

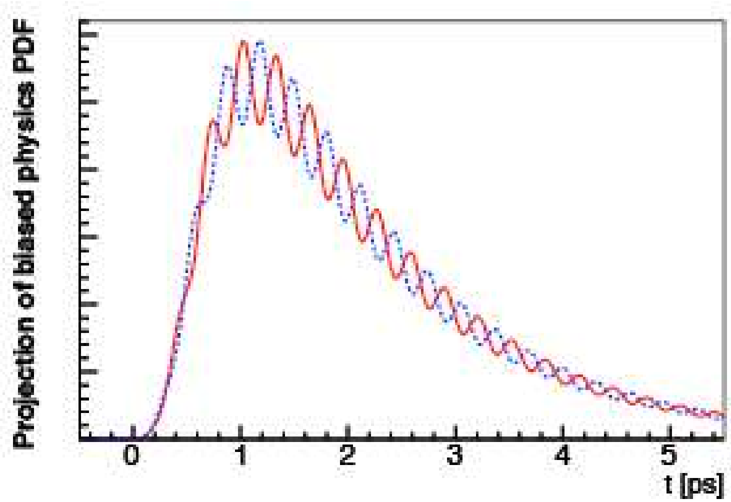
- Tagging categories: q=+1 for R($B_s^o \to f$), q=-1 for R($\bar{B}_s^o \to f$), q=0 for untagged
- D = (1-2ω) Tagging Dilution factor.

Blue: B_s^o

Red: $\bar{B}_s^o$



Transition decay rates (including ω)



With acceptance and resolution

Case:

- ΔM_s =20 ps^{-1} / /$\Delta\Gamma_s/\Gamma_s$=10% // ϕ_s= -0.4rad (10 x SM) // ω=30% // acc$_s$= 1.3 ps^{-1} // σ_t= 40fs

- Generate and fit ~ 250 toy experiments each of them corresponding to 1 year of data taking at $2fb^{-1}$

- Unbinned (extended) likelihood fit to :

$$\mathcal{L} = \prod_i \left[f_i^{\rm sig} \mathcal{L}_i^{\rm sig} + (1 - f_i^{\rm sig}) \mathcal{L}_i^{\rm bkg} \right]$$

i event and f_i^{sig} probability for each event based on of rec. mass

$\mathscr{L}_{\rm sig}$ includes decay rates, acceptance, and wrong tag fraction.

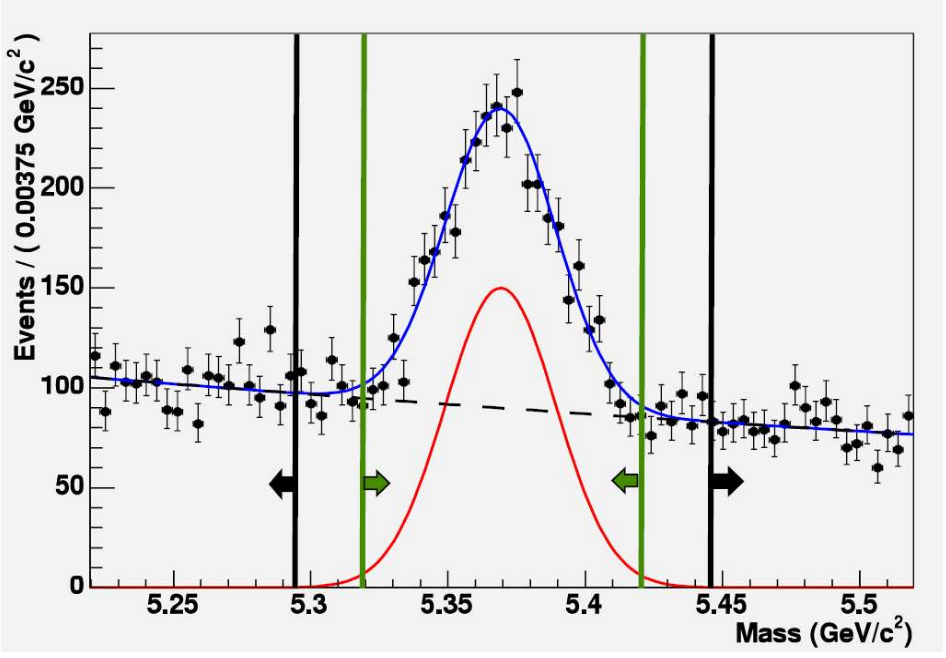
✔ Mass distributions fitted to determine signal and background probabilities that are then fixed.

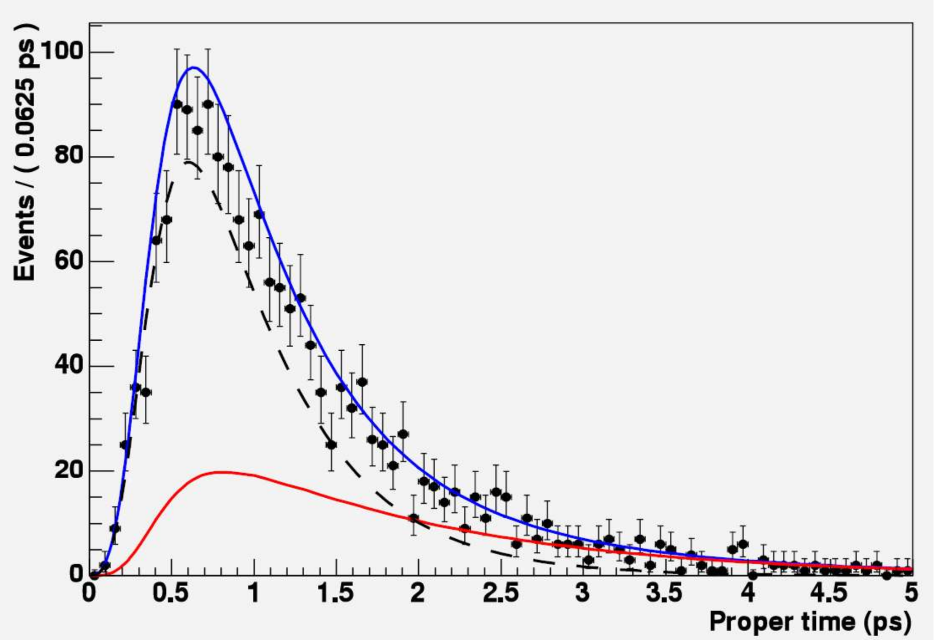
✔ Background parameters are determined from mass sidebands; acceptance function fitted and then parameters from fit fixed.

✔ From the signal window, physics parameters ($\Delta\Gamma_s/\Gamma_s$, ϕ_s , τ_{B0_s}) are extracted from the fit.

$B_s^o \to J/\Psi\,\eta'$: Likelihood fit : Mass & Rates pdfs

• PDF for the mass distribution sum of two extended likelihoods, Gaussian for signal, Exponential for background with Poisson to ensure correct proportion of signal & background in the signal region.





Red: signal // Dashed black:background // Blue: total

Green: signal region // Black: sidebands

Red: signal // Dashed black:background // Blue: total

$B_s^o \to J/\Psi\, \eta'$: Sensitivities

- Sensitivities estimated from the average of statistical uncertainties from fit results.
- Input parameters taken from Full MC simulation for each channel.
- Nominal Physics parameters as inputs values:

ϕ_s[rad]	ΔM_s [ps^{-1}]	$\Delta\Gamma_s/\Gamma_s$	τ_{B0_s}[ps]
-0.04	20.0	0.1	1.472

- Fit results: Sensitivities

Sensitivity	$J/\psi\eta(\gamma\gamma)$	$J/\psi\eta(3\pi)$	$\eta_c\phi$	$J/\psi\eta'(\eta\pi\pi$	$J/\psi\phi$
$\sigma(\phi_s)$[rad]	0.112	0.148	0.106	0.200	0.031
$\sigma(\Delta\Gamma_s/\Gamma_s)$	0.0122	0.0084	0.0084	0.0279	0.0113

$B_s^o \to J/\Psi\, \eta'$: ϕ_s expected sensitivities

- Expected sensitivities for $2fb^{-1}$ for each channel: combined value: $\sigma = \sqrt{\left(\frac{1}{\sum (1/\sigma_i^2)}\right)}$

Channel	$\sigma(\phi s)$[rad]	Contribution(σ/σ_i)[%]
$J/\psi\eta(\gamma\gamma)$	0.112	6.3
$J/\psi\eta(3\pi)$	0.148	3.6
$\eta_c\phi$	0.106	7.0
$J/\psi\eta'(\eta\pi\pi)$	0.200	1.8
Combined four pure CP eigenstates channels	0.068	18.4
$J/\psi\phi$	0.031	81.6
Combined all five CP eigenstates channels	0.028	100.0

$B_s^o \to J/\Psi\,\eta'$: Conclusions

- Able to reconstruct $B_s^o \to J/\Psi\,\eta'$; promising results, can be improved if photon reconstruction is better and proper time fitting strategies are revised.

- Contributions from pure CP eigenstates to sensitivity to ϕ_s : ~ 19%

 (Maybe other channels can help too)

- After five years (10 fb^{-1}) we reach $\sigma(\phi s)$~ 0.013 rad which is ~ 3σ of the SM value (-0.04 rad)

- If ϕ_s large compared to SM expectation ⇨ NEW PHYSICS

Back-up slides

$$B_s^o \rightarrow J/\Psi(\mu^+ \mu^-)\eta'(\pi^+ \pi^- \eta(\gamma\gamma))$$

Branching Ratio:

- $B.R.(B_s^0 \rightarrow J/\psi\,\eta')$ branching ratio still an open issue.
- η' defined as: $|\eta'\rangle = |\eta_8\rangle \sin\theta_p + |\eta_1\rangle \cos\theta_p$ (Physics Letters B,2004)
- Where η_1 & η_2 defined as:

$$\langle \eta_1 | = \frac{1}{\sqrt{3}} \langle u\overline{u} + d\overline{d} + s\overline{s} |$$
$$\langle \eta_8 | = \frac{1}{\sqrt{6}} \langle u\overline{u} + d\overline{d} - 2s\overline{s} |$$

- The value of pseudo-scalar mixing angle θ_p still controversial. Estimated to belong [-10°,-20°].
- B.R. estimated as:

$$B.R.(B_s^0 \rightarrow J/\psi\,\eta') = \left(\sqrt{\tfrac{1}{3}}\cos(\theta_p) - \sqrt{\tfrac{2}{3}}\sin(\theta_p)\right)^2 \langle J/\psi\, s\overline{s} | H_{eff} | B_s^0 \rangle = B.R.(B_d^0 \rightarrow J/\psi\, K_s)$$

$(Mixing\ Angle: \theta_p = -10°)$

$$B.R.(B_s^0 \rightarrow J/\psi\,\eta') = (4.29 \pm 0.25) * 10^{-4}$$

$$B.R._{visible}(B_s^0 \rightarrow J/\psi\,\eta') = (5.1 \pm 0.4) * 10^{-6}$$

$(Mixing\ Angle: \theta_p = -20°)$

$$B.R.(B_s^0 \rightarrow J/\psi\,\eta') = (5.74 \pm 0.34) * 10^{-4}$$

$$B.R._{visible}(B_s^0 \rightarrow J/\psi\,\eta') = (6.8 \pm 0.5) * 10^{-6}$$

$$B_s^o \rightarrow J/\Psi(\mu^+ \mu^-)\eta'(\pi^+ \pi^- \eta(\gamma\gamma))$$

Efficiencies :

$$\epsilon_{rec} = (70.0 \pm 0.4) * 10^{-2}$$

$$\epsilon_{sel} = (6.3 \pm 0.2) * 10^{-2}$$

$$\epsilon_{det} = \epsilon_{sig}^{\theta} * \left(\frac{Nsel}{Ngen}\right) * (\epsilon_{rec})^{-1} * (\epsilon_{sel})^{-1} = (5.15 \pm 0.04) * 10^{-2}$$

$$\epsilon_{sig}^{\theta} = (34.71 \pm 0.03) * 10^{-2} \quad \text{(Bmesons)}$$

$$\epsilon_{L0L1HLT} = (89.2 \pm 0.9) * 10^{-2}$$

$$\epsilon_{tag}$$

- Reconstruction Efficiency.
- Offline selection efficiency on rec'ted events
- Detection efficiency.
- Acceptance of the 400 mrad generator-level Cut.
- Combined L0&L1&HLT triggers eff. on offline select. events
- Tagging efficiency.

$$\epsilon_{total} = \epsilon_{det} * \epsilon_{rec} * \epsilon_{sel} * \epsilon_{L0L1HLT} * \epsilon_{tag}$$

$$\epsilon_{total} = (0.198 \pm 0.006) * 10^{-2} \text{(before tagging)}$$

	Before Trigger	After L0	After L0&L1	After HLT
ϵ_{tag} [%]	62.88 +/- 1.35	63.23 +/- 1.37	63.90 +/- 1.45	63.81 +/- 1.52
ω [%]	31.50 +/- 1.68	31.44 +/- 1.70	31.53 +/- 1.80	30.72 +/- 1.8
ϵ_{eff} [%]	8.61 +/- 2.02	8.71 +/- 2.0	8.72 +/- 2.20	9.49 +/- 2.37

$$\epsilon_{eff} = \epsilon_{tag}(1 - 2\omega^2)$$